TROPHIC CLASSIFICATION OF WASHINGTON LAKES USING RECONNAISSANCE DATA

STATE OF WASHINGTON
BOOTH GARDNER, Governor

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Water-Suppy Bulletin 57

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UNITED STATES GEOLOGICAL SURVEY

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METRIC (SI) CONVERSION FACTORS

Multiply	By	To obtain
acre	4047	square meter (m^2)
acre-foot (acre-ft)	1233	cubic meter (m^3)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
micromho per centimeter at 25° Celsius (umhos/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius (uS/cm at 25°C)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level; it is referred to as sea level in this report.

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ABSTRACT

A total of 134 Washington lakes were sampled to obtain information on their physical, cultural and water-quality conditions. Each lake was classified by trophic level using two methods: (1) a relative, multivariate technique based on Secchi-disc transparency and concentrations of total phosphorus, total organic nitrogen, and chlorophyll _a_ in the epilimnion; and (2) an absolute, univariate technique based on any one of three water-quality parameters: Secchi-disc transparency, total phosphorus concentration, or chlorophyll _a_ concentration.

The first method yielded a characteristic value (CV) for each lake with a range of 45 to 1,047 and median of 119, for the 134 lakes visited. The second method yielded trophic state index (TSI) values ranging from 30 to 67, 0 to 108, and 0 to 74, with medians of 44, 47, and 44 when based on Secchi disk transparency, total phosphorus, and chlorophyll _a_, respectively. In both methods, the degree of eutrophication increases as the numeric value increases. The lake rankings produced by the two methods were in general agreement, in that lakes were placed in about the same relative position using either system. Characteristic values and TSI's were also calculated for all lakes in Washington for which adequate data exist.

INTRODUCTION

Washington has more than 7,800 lakes, ponds, and reservoirs, many of which provide recreational opportunities and supply water for agricultural, industrial, and municipal uses. Many of these lakes are in or near centers of population or are influenced by areas affected by man's activities; thus, the potential for cultural eutrophication and other water-quality problems is high. It is sometimes possible to restore deteriorated lakes or to slow the deterioration process using one or more restoration techniques (Peterson and others, 1974).

In order to select lakes for restoration, however, a knowledge of the general physical features, water quality, and trophic conditions of the lakes is required. In addition, Section 314(a) of the 1972 Amendments to the Federal Water Pollution Control Act (PL 92-500) specifically requires each state to identify and classify all publicly owned fresh waters within the State according to trophic condition. This requirement was partially satisfied by the publication of Washington Department of Ecology Bulletins 42 and 43, which contain a description of water-quality conditions in many Washington lakes; the detailed references are given at the end of this report.

A preliminary water-quality characterization has also been made for more than 600 Washington lakes (Bortleson, 1978). The purpose of the study summarized in this report, initiated in July 1981 by the U.S. Geological Survey in cooperation with the Washington Department of Ecology, was to update the information contained in these earlier bulletins and to provide additional knowledge of water quality conditions in Washington lakes. The study was partially funded by the Washington Department of Ecology and the U.S. Environmental Protection Agency.

Objectives

This study was designed to (1) provide data pertaining to the physical, cultural, and water-quality characteristics of 43 lakes statewide not included in previous Geological Survey studies; (2) resample 91 lakes previously visited that either have had significant land-use changes in their drainage basins, or have significantly higher nutrient concentrations than expected in relation to the concentrations determined from previous studies; and (3) classify, according to trophic level, the 134 study lakes and all other Washington lakes for which adequate data exist, utilizing the techniques of Carlson (1977) and Bortleson (1978).

Lake Selection

Lakes not sampled previously were selected from a gazetteer of Washington lakes (Wolcott, 1973a, b) using the criteria of lake surface area, proximity to urban centers, and degree of public use. Priority was given to large lakes, close to urban centers, that were used a great deal, on the assumption that these lakes would be most susceptible to water-quality degradation. Because most lakes larger than 20 acres had already been included in previous studies, lakes of this study were generally between 15 and 20 acres.

The selection of previously studied lakes was completed by personnel of the Washington Department of Ecology, and was based in part on input by regional planners, county agents, and resource managers. These persons identified lakes in their areas of responsibility where land use has changed extensively in the drainage basins, and lakes that have developed water-quality problems since last studied. Another selection technique was to compare predevelopment concentrations of the nutrient phosphorus, as calculated using a method devised by Gilliom (1980), with actual phosphorus concentrations as measured in past studies. Those lakes showing the greatest amount of increase in phosphorus concentration have theoretically been affected the most by development and were given priority for resampling.

Occurrence of Lakes in Washington

Lakes in Washington occur under various geologic conditions. In the Puget Sound Lowland most lakes occupy depressions in the surface of glacial drift. These depressions are either elongate troughs cut by the passing ice sheet or more circular kettles formed by the melting of stagnant ice blocks. Still others are simply shallow depressions left on an irregular surface of glacial deposits.

In the adjacent foothills of the Cascade Range and Olympic Mountains, most lakes occupy depressions eroded into the bedrock by the passing continental glacier, while lakes in the higher mountains are in basins cut by local alpine glaciers.

In eastern Washington, lakes in the higher northern areas—the Okanogan Highlands and Selkirk Mountains—and on the eastern slope of the Cascade Range generally occur in glacier-cut depressions in bedrock. In the semiarid Columbia Plateau, underlain by basalt, most lakes occupy the more deeply cut parts of coulees of the Channeled Scablands. Most of these coulees were cut by gigantic, catastrophic floods (Bretz, 1959) resulting from the breaking of ice dams and the rapid emptying of large glacial lakes.

Many lakes have been formed, or increased in size, by man's activities. Numerous reservoirs are located in mountain valleys and serve a variety of purposes, including municipal water supply, irrigation, electrical-power generation, flood control, and recreation. In lowland areas, some natural lakes have been enlarged and new lakes have been formed by small dams. In the Columbia Basin Irrigation Project area of eastern Washington, several lakes have been enlarged and reservoirs have been created in conjunction with large-scale irrigation by water diverted from the Columbia River at Grand Coulee Dam. Also, numerous small lakes and ponds have resulted from irrigation in the area.

More detailed discussions of lake formation are provided by Hutchinson (1957) for lakes in general, and by Dion (1978) for Washington lakes.

The physical, cultural, and water-quality parameters used to describe the individual lakes studied in 1981 are explained in this section in the sequence in which it appears on the data sheet in Appendix A. An index to Appendix A begins on page 317, and indicates which of the 1981 study lakes had been studied previously and which had not. The definitions of numerous limnological and hydrological terms used throughout the report are provided in the Glossary (p. 24).

General

Lake name. The lake name was taken from Geological Survey topographic maps. Duplicate lake names within a single county are followed by location (township, range, and section) designations for uniqueness. The proper name of the lake is given first; in common usage, however, the term "Lake" may either preceed or follow the lake name. All adjectives (for example, Big, East, and Lower) follow the lake name. When a lake has two names, both are given, but priority is given to the topographic-map name. The lake names and respective data are listed alphabetically by counties.

Drainage basin. The river drainage basin in which the lake is located is designated by a Water Resources Inventory Area (WRIA) number as established by the Washington Department of Ecology. The WRIA numbers and names are listed in table 1.

Location. The township, range, section, latitude, and longitude were determined from Geological Survey topographic maps. The location point is the lake outlet; for lakes without outlets, the southernmost shoreline point was used. The lakes are presented in the report according to the county in which the location point is found.

Bathymetric map. A bathymetric map is presented for each lake, including the source, the scale of the map, and the date of preparation.

Aerial photographs. Oblique black-and-white aerial photographs, taken at the time of visit, are presented for most lakes. Vertical black-and-white aerial photos, obtained from the Washington Department of Natural Resources, are used only if suitable oblique photos were not available.

TABLE 1.--Water-resource inventory areas of Washington

WRIA Number	WRIA Name	WRIA Number	WRIA Name
01	Nooksack	32	Walla Walla
02	San Juan	33	Lower Snake
03	Lower Skagit-Samish	34	Palouse
04	Upper Skagit	35	Middle Snake
05	Stillaguamish	36	Esquatzel Coulee
06	Island	37	Lower Yakima
07	Snohomish	38	Naches
08	Cedar-Sammamish	39	Upper Yakima
09	Duwamish-Green	40	Alkali-Squilchuck
10	Puyallup-White	41	Lower Crab
11	Nisqually	42	Grand Coulee
12	Chambers-Clover	43	Upper Crab-Wilson
13	Deschutes	44	Moses Coulee
14	Kennedy-Goldsborough	45	Wenatchee
15	Kitsap	46	Entiat
16	Skokomish-Dosewallips	47	Chelan
17	Quilcene-Snow	48	Methow
18	Elwha-Dungeness	49	Okanogan
19	Lyre-Hoko	50	Foster
20	Soleduck-Hoh	51	Nespelem
21	Queets-Quinault	52	Sanpoil
22	Lower Chehalis	53	Lower Lake Roosevelt
23	Upper Chehalis	54	Lower Spokane
24	Willapa	55	Little Spokane
25	Grays-Elochoman	56	Hangman
26	Cowlitz	57	Middle Spokane
27	Lewis	58	Middle Lake Roosevelt
28	Salmon-Washougal	59	Colville
29	Wind-White Salmon	60	Kettle
30	Klickitat	61	Upper Lake Roosevelt
31	Rock-Glade	62	Pend Oreille

Physical

Physical data were collected from topographic maps, bathymetric maps, and aerial reconnaissance from a helicopter. Drainage areas and lake altitudes were determined from topographic maps. Bathymetric maps were used to calculate such morphometric parameters as area, volume, mean depth, maximum depth, shoreline length, shoreline configuration, development of volume, and bottom slope.

The physical characteristics of lakes are presented not only because they may influence the trophic status of the lakes, but because they provide values by which lakes may be compared. Further discussions of the determination of morphometric parameters and their significance are presented by Dion (1978) and most textbooks on limnology (for example, Hutchinson, 1957, and Wetzel, 1975).

Drainage area. The drainage area that contributes runoff water to each lake was computed from Geological Survey maps, based on topographic divides. Some lakes are in drainage basins where rainfall is so low that surface-water runoff to the lake may not be a significant factor.

Altitude. The altitude of the lake water surface above sea level was determined from topographic maps.

Lake area (A). The surface area of the lake, in acres, was obtained from the lake outline on the bathymetric map. Because lake area can vary between seasons and from year to year, the area figures reported (as well as other morphometric data) are intended only to describe the general size of the lake.

Lake volume (V). Lake volume, in acre-feet, was obtained by computing and then summing the volumes of each stratum of water between successive contours on the bathymetric map.

Mean depth ($\bar{Z}$). The mean depth for a lake is obtained by dividing the volume of the lake by its area. It represents, in a single quantity, a relationship between depth, volume, and area, and can be used in comparing lakes.

Maximum depth (Z_m). The greatest depth of the lake as determined from the bathymetric map.

Shoreline length (L). The distance around, or perimeter of, the water surface touching the shore (zero contour line), as shown on the bathymetric map. The shoreline length is used in calculation of shoreline configuration.

Shoreline configuration (D_L) (also called shoreline development). A dimensionless ratio of shoreline length to the circumference of a circle having an area equal to that of the lake, given as

$$D_L = \frac{L}{\sqrt{2\pi A}}$$

This quantity is an index of the potential for littoral, or near-shore, geological and biological processes to affect the lake. Nearly circular lakes have values near unity, oval or irregularly shaped lakes have higher D_L values, and very elongated lakes have the highest D_L values. High values for shoreline configuration suggest the presence of inlets and protected bays--areas suitable for plant growth--and also indicate an increase in contact between land and water. Therefore, shoreline configuration is often an indirect indicator of plant growth capacity and enrichment potential from nearshore development and runoff.

Development of volume (D_V). The development of volume is defined as the ratio of the mean depth ($\bar{Z}$) to the maximum depth (Z_m), and represents an expression of the form or shape of the lake basin as related to lake volume. Lakes with a low D_V ratio are usually cone-shaped depressions, and lakes with a high D_V ratio are steep-sided with flat bottoms. Shallow flat-bottomed lakes, which have high D_V values, tend to provide a greater opportunity for exposure of nutrient-rich bottom sediments to light and warmer, near-surface water, which in turn could stimulate phytoplankton growth in the overlying water.

Bottom slope (Z_r). Bottom slope is a percentage ratio of the maximum depth of a lake to its surface area, expressed as the mean lake diameter. It is calculated from the equation

$$Z_r = \frac{88.6\ (Z_m)}{\sqrt{A}}$$

Lakes with high bottom slopes will have a small surface area relative to the maximum depth. Thus, bottom slope is a measure of the extent of shallow water, which is important to the growth of rooted aquatic plants and to the potential for wind mixing of bottom sediments with the overlying water. This quantity is sometimes referred to as relative depth (Hutchinson, 1952).

Surface inflow. The presence or absence of a surface inflow of water, as determined from maps or by aerial reconnaissance, is indicated. However, even though no inflow may be indicated, a surface inflow may in fact be present at other times of the year, or may have been present but not seen from the air because of heavy vegetation. Some lakes have no surface inflow, and water gain is by direct precipitation and (or) ground-water seepage.

Surface outflow. The presence or absence of a surface outflow of water, as determined from maps or by aerial reconnaissance, is indicated. The presence of a dry outflow channel was considered to constitute an outflow for purposes of this report. As with inflows, outflows may be present only during part of the year, or the channel may not have been visible at the time of aerial reconnaissance. Some lakes have no surface outflow, and water loss is by evaporation, transpiration, and (or) ground-water seepage.

Cultural

Data related to cultural development were obtained from topographic maps, aerial photographs, and aerial reconnaissance of the shoreline. These data give a general indication of the potential for nutrient loading to a lake. For example, a lake with a large number of nearshore homes and a relatively high percentage of residential development in the drainage basin will be more likely to receive nutrient inputs, and at higher concentrations, than a lake with few or no homes along the shore.

Nearshore residential development. The percentage of shoreline occupied by residential development.

Number of nearshore homes. A count of the number of nearshore homes adjoining the lakefront.

Land use in drainage basin. The drainage basins of the lakes were partitioned into various generalized land use categories. Values given reflect the percentages of the basin used primarily for forest or for residential urban, residential suburban, or agricultural development. The lake surface is also given as a percentage of the total drainage basin. A general description of the land-use categories is as follows:

a. Residential urban.--Predominant use is for single-family residences, although apartment complexes and commercial or industrial activities also may be present.

b. Residential suburban.--Predominant use is single-family residences.

c. Agricultural.--Pasture or cropland.

d. Forest or unproductive.--Public and private forest lands and tree farms. Lands may include cleared or fallow unproductive land, meadows, wetlands, and recreational areas.

e. Lake surface.--Includes the surface area of the study lake and of upstream tributary lakes.

Public boat access to lake. The presence of a public boat access access is shown on the bathymetric map (symbol, black triangle).

Water Quality

Water-quality samples were collected from each lake during June and July 1981 using a float-equipped helicopter, except for three lakes which were sampled by boat in September 1981.

Vertical profiles of temperature and dissolved-oxygen concentration were made over the deepest part of the lake as determined from bathymetric maps or by sounding. Discrete samples were taken 3 feet below the water surface and 3 feet above the lake bottom for the determination of specific conductance, pH, and nutrient concentrations. Lakes less than 7 feet deep were sampled only at the 3-foot depth. The transparency of the water was determined by Secchi disc.

The collection of biological data involved sampling from the 3-foot depth for the determination of chlorophyll _a_ concentration, and a low-level aerial reconnaissance of the lake surface and shoreline to determine the extent of macrophyte coverage.

All samples were collected and analyzed according to accepted standardized procedures (Greeson and others, 1977; Skougstad and others, 1979; American Public Health Association and others, 1980).

> _Water temperature_. Water temperature, which varies in lakes with depth and time of year, is an important controlling factor for life processes and chemical-reaction rates, as well as many physical events that occur in the aquatic environment. For some lakes, the water temperatures listed for the upper, near-surface water were probably close to the maximum for the year. Temperature profiles in lakes during midsummer generally follow one of two common patterns. In shallow lakes, well exposed to the wind, temperatures are practically constant from top to bottom. This uniformity of temperature indicates that the water is well mixed throughout. The other common pattern occurs in deeper lakes, where three characteristic thermal layers, or zones, are present: (1) an upper zone (epilimnion) of warmer water in which temperature is more or less uniform throughout; (2) an intermediate zone (metalimnion) in which temperature declines rapidly with depth; and (3) a lower zone (hypolimnion) of colder water in which temperature is again more or less uniform throughout. This thermal relationship (warmer water at surface and colder water near bottom) prevents vertical mixing of the lake.
>
> Of special significance is the temperature of the hypolimnion compared to the epilimnion during midsummer, because (1) temperature stratification and the resultant lack of water circulation affect the vertical distribution of nutrients, and (2) water temperatures affect the potential of cold-water fisheries resources.

A more detailed discussion of thermal relationships in lakes is presented by Dion (1978).

Dissolved oxygen. The concentration of DO (dissolved oxygen) in a lake varies with time of year and depth of water, and is a function of many factors, including the water temperature, atmospheric pressure, and salinity of the water. Oxygen concentration in water is continually being altered by life processes, such as photosynthesis and respiration, and by complex chemical reactions. Of special biological significance is the amount of DO in the hypolimnion during midsummer. The organisms in the lighted upper layers of water produce organic matter that eventually settles to the bottom, where bacteria consume oxygen to degrade the organic materials, thereby reducing the DO concentration in the hypolimnion. Thus, the hypolimnetic-oxygen deficit frequently is related to the biomass or plant growth in the upper water (Hutchinson, 1957). For good growth and general health of trout, salmon, and other species of cold-water biota, the DO concentrations should not be less than 6.0 mg/L (milligrams per liter) according to the Federal Water Pollution Control Administration (1968). The U.S. Environmental Protection Agency (1977) has established a criterion of 5 mg/L as the minimum dissolved concentration required to maintain a "good fish population."

Specific conductance. Specific conductance is a measure of the water's ability to conduct an electric current, and is expressed in micromhos per centimeter (umho/cm) at 25°C (25 degrees Celsius). Because the specific conductance is related to the concentration and chemical types of ions in solution, it can be used for approximating the dissolved-solids concentration in the water. The purer the water, the greater its resistance to electrical flow, and the lower the specific conductance value. In general, lakes drained by outflow channels have low conductivities, reflecting the relatively rapid rate of water movement from inflows to outflow. In those lakes lacking significant outflow channels, the ionic composition of the water is, in large part, dependent on concentration effects due to evaporation from the lake surface. The specific conductance of water in western Washington lakes usually ranges from 25 to 100 umho/cm and in eastern Washington lakes from 100 to 400 umho/cm, except in the Columbia Basin, where the values range from 400 to 800 umho/cm.

pH. pH is the negative logarithm of the hydrogen-ion concentration, expressed as a number from 0 to 14. A pH of 7 is neutral, a pH less than 7 is acidic, and a pH greater than 7 is basic.

The Environmental Protection Agency (1977) has established a pH range of 6.5 to 9.0 as being satisfactory for the well-being of freshwater fish and invertebrate fish-food organisms. While the pH of a water may not directly affect all living organisms, the toxicity of some compounds increases when the pH is very low or very high. Additionally, in association with anaerobic conditions (very little or no dissolved oxygen), changes in pH affect the solubility of nutrients and some metallic elements (iron, manganese, and aluminum, for example) found in lake sediments.

Nutrients. A nutrient is any chemical element, ion, or compound that is required by an organism for the continuation of growth, reproduction, and other life processes. Many elements and compounds act as nutrients to supply the food for aquatic plants. Nitrogen and phosphorus, however, usually are considered the limiting nutrients for aquatic plant growth—algae in particular—and as such, were the only nutrients considered in this study. Whatever nutrient is limiting algal growth, the concentrations of nitrogen and phosphorus are useful in evaluating the trophic conditions of a lake (Lee, 1972). The nutrient concentrations that were determined at top and bottom sampling depths included total nitrate, total nitrite, total ammonia, total organic nitrogen, total nitrogen, dissolved orthophosphate, and total phosphorus.

Water transparency. Water transparency is usually expressed in terms of Secchi-disc transparency, which is the depth at which a black-and-white disc (8 inches in diameter) disappears from view when lowered into the water. Because changes in biological production can cause changes in the color and turbidity of a lake, Secchi-disc transparency often is used as a gross measure of the quantity of plankton in the water. Secchi-disc depths preceded by the symbol ">" indicate the disc was resting on the bottom of the lake and was still visible.

Chlorophyll *a*. Chlorophyll *a* is a green photosynthetic pigment present in all groups of algae. The concentration of chlorophyll *a* is frequently used in estimating the productivity level of a lake and in quantifying its trophic state. The chlorophyll *a* values reported on the data sheets have been adjusted to exclude contributions from phaeophytin, a pigment formed when chlorophyll breaks down.

Aquatic macrophytes. Aquatic macrophytes are plants that have roots, stems, and leaves and can usually be seen with the unaided eye.

Estimates of the percentage of both the littoral (shoreline) and water-surface (entire lake) zones covered by emersed and (or) floating aquatic macrophytes were made by visual inspection during the aerial reconnaissance.

TROPHIC CLASSIFICATION

The very broad nature of the traditional classification categories of oligotrophic, mesotrophic, and eutrophic makes them inadequate for all but the most general of uses. Shapiro (1975) argued that in order to properly identify and manage lakes, to estimate their recreational potential, to estimate their sensitivity to degradation, and to restore them efficiently, the lakes should be classified with quantitative trophic indices. Shapiro further suggested that what limnology needed was a classification system analogous to the Richter scale used to describe earthquakes—an objective, numerical scale whose derivation might not be understood by all, but whose significance has come to be appreciated through use. In recent years, numerous lake-classification schemes have been developed.

As part of this investigation, all Washington lakes for which adequate data exist were classified trophically using two methods. One method utilized principal-component analysis to derive a characteristic value (CV) for each lake. The characteristic value concept was developed by Bortleson (1978) specifically for Washington lakes, using data from 617 lakes. It is both relative and multivariable in nature. In a relative classification scheme, classes are based on analysis of the data base; that is, lakes are classified with respect to one another.

The other method yielded trophic state indices (TSI's) for each lake. The TSI system was developed for Minnesota lakes (Carlson, 1977), but has since proven to have broad geographic applicability. It is both absolute and univariate in nature, although in theory the same TSI number can be calculated using any one of three variables.

An absolute classification scheme is composed of predefined classes that do not depend on the data base. Such a scheme is simpler to use than a relative scheme, and new lakes can be added without changing the structure of the classification.

Characteristic Value (CV)

Principal-component analysis examines a set of data so that linear relationships between variables are obtained that account for the variation within the data. The first principal component accounts for the largest percentage of the variance in the data, with each succeeding principal component accounting for smaller and smaller percentages. As many principal components can be determined as there are variables. The results of the analysis yield vectors, the elements of which are the correlations of each variable with the components, and also the amount of the total sample variance represented by each component. A more thorough discussion of the theoretical basis and computational methods for principal-component analysis can be found in Morrison (1967). Applications of principal-component analysis to hydrology (and lake classification in particular) may be found in Shannon and Brezonik (1972), Bortleson (1978), and Ciecka and others (1980).

In this study, four water-quality variables were used in the principal-component analysis: Secchi-disc transparency, and concentrations of total organic nitrogen, total phosphorus, and chlorophyll a in the epilimnion. These variables were selected because they are commonly used to characterize the trophic conditions of lakes (Shannon and Brezonik, 1972; Bortleson, 1978; and Chapra and Dobson, 1981). It should be noted that in the original development of the CV concept, Bortleson did not include the variable chlorophyll a because chlorophyll data were not available for most lakes.

The equation for determining CV, which follows, was derived using the methods described by Bortleson (1978) and Shannon and Brezonik (1972).

$$CV = 73.7\,(TON-1.05) + 304\,(TP-0.057) + 159\,(1/SD-0.47) + 3.35\,(Chl-8.38) + 178.4 \qquad (1)$$

where

CV = characteristic value,
TON = total organic-nitrogen concentration of epilimnion, in mg N/L (milligrams of nitrogen per liter)
TP = total phosphorus concentration of epilimnion, in mg P/L (milligrams of phosphorus per liter),
SD = Secchi-disc transparency, in meters, and
Chl = chlorophyll a concentration of epilimnion, in ug chl a/L (micrograms of chlorophyll a per liter).

Lakes with higher CV's are generally considered to be more "eutrophic" than lakes with lower CV's.

Characteristic values for each of the 134 lakes sampled as part of this study are given on the individual lake data sheets (Appendix A) and are listed in aggregate in Appendix B. Appendix C lists CV's calculated by Bortleson (1978) for 616 lakes and, where appropriate data exists, TSI's for an additional 160 lakes.

Trophic-State Index

Because a TSI number can be calculated using any one of three variables, Reckhow (1979) believes the method is actually multivariate. Carlson (1979) also stated that his method could be made multivariable by averaging the three TSI's (but if one of the TSI's diverged significantly from the other two, it would be difficult to detect the divergence in the average value). However, the use of a single variable upon which to base a trophic state index greatly simplifies data collection and, according to Wentz (1981), leads to less ambiguity than do indices based on several variables. A disadvantage of the single-variable approach is that as fewer variables are used, the index becomes more unstable. Shannon and Brezonik (1972) present the example that if phytoplankton biomass was the sole criterion, lakes with a dense macrophyte and (or) periphyton population but low phytoplankton population would be misclassified as "oligotrophic."

Carlson's TSI was developed by first assigning a TSI range of 0-100 to the largest range of Secchi-disc depth that could reasonably be expected (0-210 ft), such that a halving or doubling of the Secchi-disc depth corresponded to a change of 10 units in TSI. Regression equations were then used to relate the TSI to concentrations of total phosphorus and chlorophyll a. Because of this regression approach, values of TSI greater than 100 are not uncommon for trophic determinations based on total phosphorus.

TSI values are calculated from Secchi-disc depth and concentrations of total phosphorus and chlorophyll a as follows:

$$TSI_{(SD)} = 10\left(6 - \frac{\ln SD}{0.693}\right) \qquad (2)$$

$$TSI_{(TP)} = 10\left(6 - \frac{\ln \frac{48}{TP}}{0.693}\right) \qquad (3)$$

$$TSI_{(Chl)} = 10\left(6 - \frac{2.04 - 0.68 \ln Chl}{0.693}\right) \qquad (4)$$

where

SD = Secchi-disc depth, in meters,
TP = total phosphorus concentration of epilimnion, in ug P/L (micrograms of phosphorus per liter), and
Chl = chlorophyll a concentration, in ug chl a/L.

Carlson (1977) suggested that for purposes of classification in summer, priority should be given to the chlorophyll index. In spring, autumn, and winter, when algal growth may be limited by factors other than phosphorus, priority should be given to the total phosphorus index. These priorities would result in about the same TSI during any season of the year.

TSI values for the 134 lakes sampled as part of this study are given on the individual lake data sheets (Appendix A) and in Appendix B. As in the Bortleson method, lakes with higher TSI values are normally considered more "eutrophic" than lakes with lower values.

As might be expected, the TSI values determined separately from the three parameters do not always coincide for an individual lake. Shapiro (1975) points out that this does not necessarily mean that some of the index values are wrong, but may indicate instead certain facts about the individual lake's behavior. For example, if the $TSI_{(TP)}$ is higher than the $TSI_{(SD)}$ or $TSI_{(Chl)}$, it could indicate either that the lake is not phosphorus-limited, or that grazing by herbivorous zooplankton is sufficient to keep algal populations at a low level.

The advantages of Carlson's TSI method are that it is simple, uses easily obtained data, is highly objective, the raw data can be retrieved from the index values, and additional lakes may be indexed at any time.

Summary of Trophic Values

Ranges and median values of CV and of TSI for both 1981 and pre-1981 lake data are presented in table 2 for purposes of summary. Although 91 lakes were previously visited, only 85 had been included by Bortleson (1978) in the data set used to develop the CV concept. The data in table 2 should be used only to obtain an overview of the CV's and TSI's for each group of lakes, and not as a statistical comparison between lakes through time.

On the basis of comparisons with other methods of classifying lakes, Carlson (1979) has suggested limits of TSI values that correspond to the traditional terms "oligotrophic" and "eutrophic." He found that a mean TSI value of 41 (with a standard deviation of 5.8) was the upper limit of oligotrophy, and a mean TSI value of 51 (s.d. = 7.6) was the lower limit of eutrophy. Although these suggested guidelines are of limited use when applied to the median value of a large number of lakes, they are of considerable use in estimating the likely trophic levels of the individual lakes described in Appendix A and in describing the "trophic range" of the study lakes in aggregate.

TABLE 2.--Ranges and median values of CV (characteristic value) and TSI (trophic state index)

	Pre-1981[1]			1981[2]		
Index	Number of lakes	Median	Range	Number of lakes	Median	Range
CV:						
Original	[3]617	55	1-1,259	85	106	46-77
Newly visited	--	--	--	49	157	45-1,047
Total	--	--	--	134	119	45-1,047
TSI:						
SD[4]	712	46	12-93	134	44	30-67
TP[4]	775	47	4-142	134	47	0-106
Chl[4]	99	45	27-65	134	44	0-74

[1]Pre-1981 CV values are based on Secchi-disc transparency and concentrations of total organic nitrogen and total phosphorus.

[2]1981 CV values are based on Secchi-disc transparency and concentrations of total organic nitrogen, total phosphorus, and chlorophyll *a*.

[3]Original method data base.

[4]$TSI_{(SD)}$, $TSI_{(TP)}$, and $TSI_{(Chl)}$ refer to the trophic state index based on Secchi-disc transparency, total phosphorus, and chlorophyll *a* concentrations, respectively.

The TSI system appears to be the most meaningful way to classify a lake or group of lakes, because the system is absolute and univariate in nature. However, the choice of variable on which to base the system is very important, and without a knowledge of the chemical and biological processes occurring in a lake, the resulting TSI number may be misleading. A problem of interpretation is also present when two or more TSI's are determined for a lake; that is, how to reconcile differing TSI's. Although an average of the different TSI's for a lake yields a single number, some advantages of a univariate classification are lost.

Because the CV of a lake is a relative value, the assignment of trophic names (oligotrophic, eutrophic, etc.) to a particular range of CV's is not recommended. The method can be used, however, to detect temporal changes of trophic level in individual lakes and to compare trophic levels of two or more lakes.

A comparison of TSI's using pre-1981 data with TSI's calculated from 1981 data can be done for specific lakes using Appendix B. For example, in 27 lakes, $TSI_{(SD)}$ decreased (indicating an improvement in Secchi-disc transparency), while $TSI_{(TP)}$ increased (indicating increased total phosphorus concentration in the epilimnion). One possible explanation for this relationship may be that some nutrient other than phosphorus is limiting the growth of phytoplankton in these 27 lakes.

However, comparisons of only two trophic assesments made several years apart are probably inadequate to detect long-term changes in trophic level. In addition, short-term fluctuations of nutrient concentrations, suspended matter, and biological activity undoubtedly occur because of varying climatic, hydrologic, and chemical conditions, so a trophic designation based on a single sample in time may not reliably represent the long-term trophic status of a lake.

It should also be emphasized that, because the range in CV units for the 1981 study was approximately 10 times that of the TSI range (see table 2), CV and TSI units should not be equated or compared.

To determine the degree of similarity of relative lake rankings as determined by both classification methods, the lakes were listed by order of increasing trophic number calculated from each equation (1981 CV, Bortleson's CV with 1981 data, $TSI_{(SD)}$, $TSI_{(TP)}$, and $TSI_{(Chl)}$). The calculation of CV's from data not used in the derivation of Bortleson's original equation was based on the assumption that, because the new data were within the range of those used to develop the original equations, any discrepancies would be minor and the overall interpretation would be valid. Spearman's rank-correlation coefficients were then calculated for all possible pairs of rankings. The coefficients provided an indication of the similarity in the ranking of the lakes as determined by each equation. A coefficient (r value) of 1.0 indicates that the two classification methods have ranked the lakes in exactly the same order, even though the actual trophic numbers (CV or TSI) differ in magnitude. Less perfect correlations would produce coefficients of less than 1.0.

The following matrix present the correlation coefficients calculated for the pairs of rankings.

	1981 CV	Bortleson CV	TSI_{TP}	TSI_{SD}	TSI_{Chl}
1981 CV	1.0	0.90	0.66	0.90	0.79
Bortleson CV		1.0	0.54	0.67	0.53
TSI_{TP}			1.0	0.60	0.52
TSI_{SD}				1.0	0.81
TSI_{Chl}					1.0

As might be expected, the 1981 CV's compare well with the Bortleson CV's using 1981 data (r = 0.90). The 1981 CV's also compare well with TSI(SD)'s and TSI(Chl)'s (r = 0.90 and r = 0.79, respectively); the correlation is not as good with TSI(TP) (r = 0.66) but it is still significant (α= 0.01; that is, the probability that there is no correlation is 1 percent).

The matrix also indicates that the correlation coefficients between lakes listed by TSI(TP) and the other TSI numbers are relatively low. One possible explanation for the low correlations is that phosphorus may be present in the lakes but not associated with algal biomass (as measured by Secchi-disc transparency and (or) chlorophyll a concentration).

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GLOSSARY

Acre-foot. The volume of water required to cover 1 acre to a depth of 1 foot, and equal to 43,560 cubic feet or 325,900 U.S. gallons.

Bathymetric. Relating to the measurement of water depths, as for a lake.

Biomass. The total amount of living material in a particular habitat or area.

Chlorophyll *a*. A green pigment that is found in all types of algae and is partly responsible for photosynthesis.

Coulee. A short gulch or water channel.

Drainage area. The area drained by, or contributing to, a stream, lake, or other surface-water body.

Drift. Any rock material transported and deposited directly or indirectly by a glacier.

Epilimnion. The upper, relatively warm, circulating zone of water in a thermally stratified lake.

Eutrophic. Pertaining to waters in which production is high as a consequence of a large supply of available nutrients.

Herbivore. An organism that feeds on plants.

Hypolimnion. The lower, relatively cold, non-circulating water zone in a thermally stratified lake.

Kettle. A basin formed by the melting of a detached mass of glacial ice buried or submerged in glacial drift.

Limnology. The science or study of inland bodies of water, such as lakes.

Littoral. The shoreward region of a body of water, where light penetrates to the bottom.

Macrophyte. A plant that can be seen with the unaided eye.

Mean depth. A morphometric parameter of a lake obtained by dividing the volume by the area.

Mesotrophic. Pertaining to waters in which production is moderate.

Metalimnion. The middle layer of water in a thermally stratified lake, in which temperature decreases rapidly with depth; also called the thermocline.

Morphometric. Pertaining to the measurement of the shape characteristics of lakes and lake basins.

Nutrient. Any chemical element, ion, or compound required by an organism for the continuation of growth, reproduction, and other life processes.

Oligotrophic. Pertaining to waters in which production is low as a consequence of a small supply of available nutrients.

Periphyton. Aquatic microrganisms that are attached to, or live upon, submerged surfaces.

pH. The negative logarithm of the hydrogen-ion concentration; it is used to indicate the relative acidity or alkalinity of a solution.

Photosynthesis. The process by which chlorophyll-bearing plants use energy from the sun to convert water and carbon dioxide into carbohydrates.

Phytoplankton. The plant part of the plankton.

Plankton. Suspended or weakly swimming aquatic organisms.

Productivity. The total amount of living matter produced in an area per unit of time, regardless of the fate of the living matter.

Regression. A statistical method of determining the relationship between one variable and one or more other variables.

Relative depth. A morphometric parameter of a lake defined as the ratio of the maximum depth to the mean lake diameter, in percent.

Scablands. Areas where erosion has removed the soil and the underlying rock is exposed or covered largely with its own coarse debris.

Secchi disc. A disc, usually 8 inches in diameter and painted in alternating white and black quadrants, used to measure light transparency in lakes.

Shoreline configuration. A morphometric characteristic of a lake defined as the dimensionless ratio of the shoreline length to the circumference of a circle having the same area as the lake.

<u>Specific conductance</u>. The measure of a water's ability to conduct an electric current, usually expressed as micromhos per centimeter at 25° Celsius.

<u>Till</u>. A nonsorted, nonstratified glacial deposit usually composed of gravel, sand, silt, and clay.

<u>Transpiration</u>. The process by which water vapor escapes from a living plant and enters the atmosphere.

<u>Trophic</u>. Pertaining to the relative level of production of a water body, such as a lake.

<u>Zooplankton</u>. The animal part of the plankton.